Pulsed-power based bright EUV light source for metrology

Sergey V. Zakharov

NaextStream sas, Buc, France

sergey.zakharov@naextstream.com

NAEXTSTREAM

+ *also with NRC Kurchatov Institute , Moscow, Russia*

Sources for EUV & Beyond Lithography

Diffraction restricts the resolution

$$r \geq k_1 \frac{\lambda}{NA}$$

NOW
EUV for HVM
beyond 16 nm

$\lambda \Rightarrow$ 13.5nm $\Rightarrow$ 6.Xnm
($h\nu$=92eV $\Rightarrow$ 185eV)

$\delta\lambda/\lambda \Rightarrow$ 2%

Nano-Age World

The optics is made of
multi-layer mirrors
with reflection efficiency ~70%

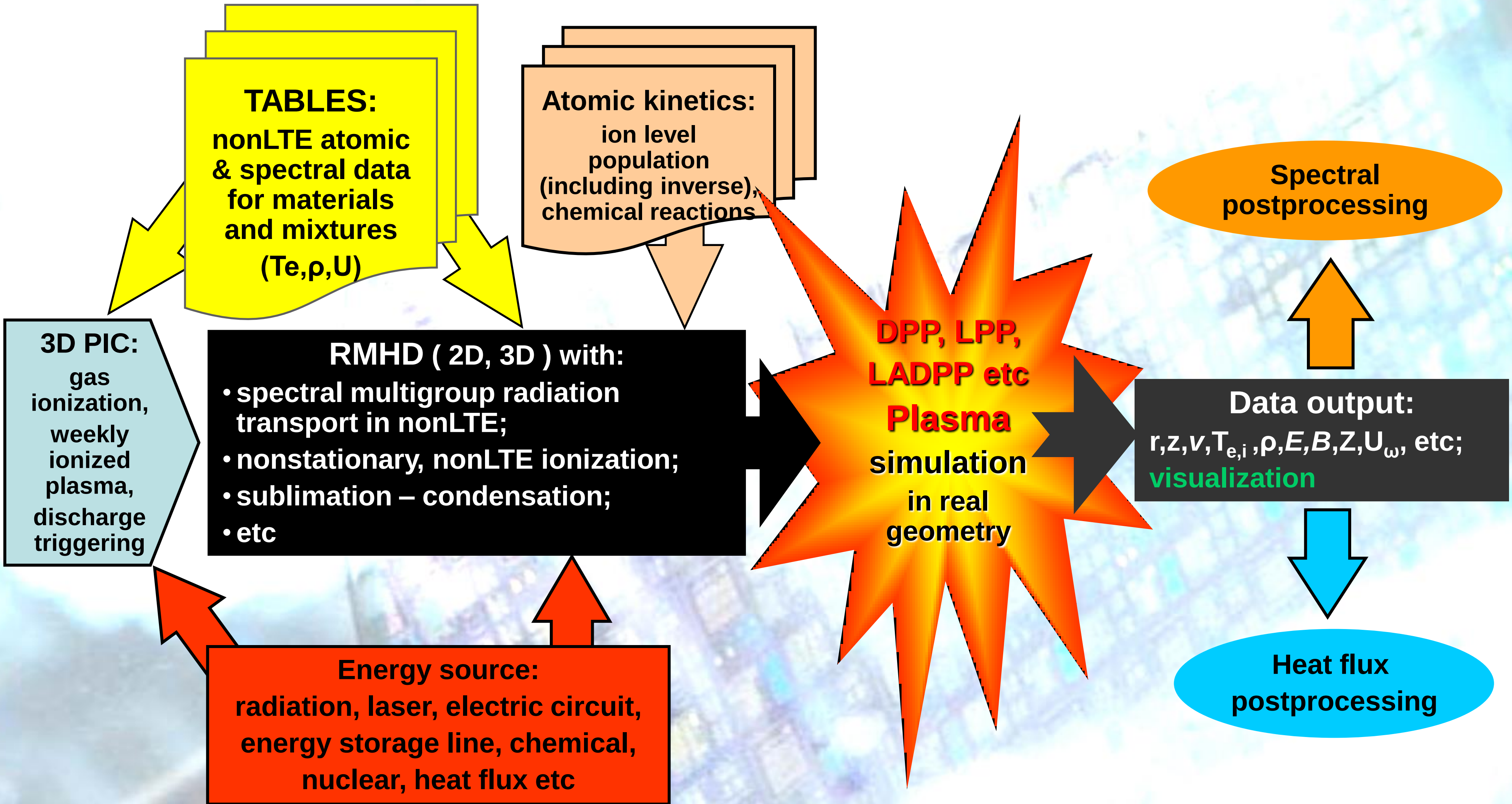
- For HVM: >> 200 W of in-band power at IF within < 3mm^{2}sr etendue
- For mask inspections ABI$\rightarrow$AIMS$\rightarrow$APMI : 30 $\rightarrow$ >100 W/mm$^2\cdot$sr

Sn (4d-4f), Xe (5p-4d) … High Energy Density plasma
(T_e=20-40eV) radiates in EUV range
LPP & DPP

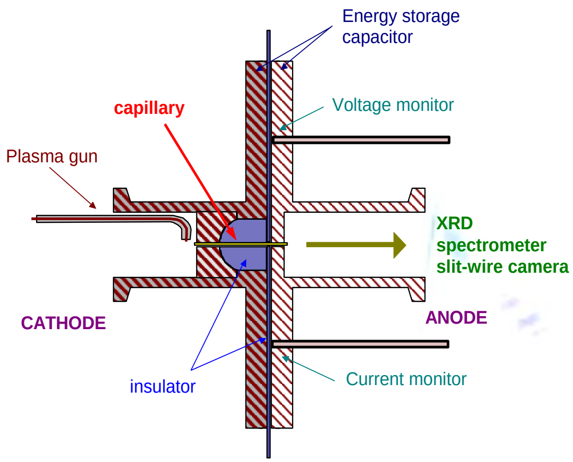
ZETA → Z* RMHD → ZENITH Code

multi-physics model

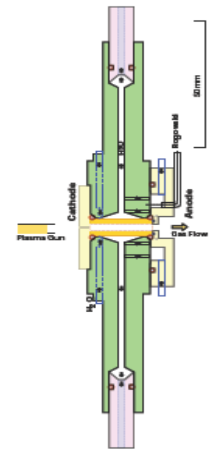
NAEXTSTREAM



Hollow cathode capillary discharge EUV sources



Original EPPRA design
- low inductance
- solid insulator
- fast pulse
- high photon collection efficiency



PUC design
- low inductance
- water: insulator & cooling agent
- medium pulse
- high CE~1.6% in Xe
- lower frequency operation

– pulse charged local energy storage

– sub-mm diameter capillary

– hollow cathode e-beam for on-axis discharge initiation

– rapid current heating

– small high energy density radiation emitter

NanoUV design
- high inductance
- capacitor array
- slow pulse
- low instant power

Bright EUV plasma source
pulsed-power capillary discharge

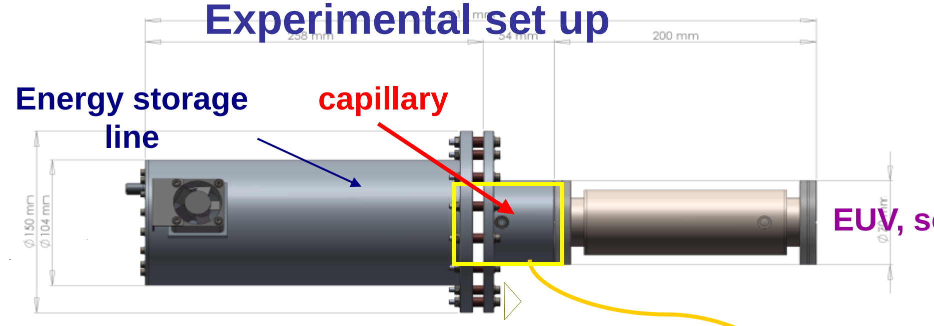
Pulsed-power

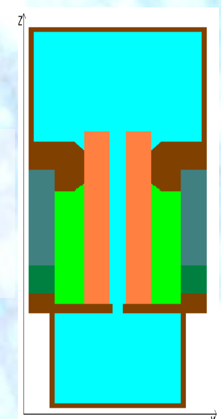
Energy storage line	1 – 5 J
Liquid dielectric & coolant	
Voltage	20-30 kV
Current	10 - 20 kA
Pulse	~15-30 ns
Capillary dimension	∅ 1.6 - 3.2 mm
	L = 12-18 mm

Operation frequency 1 - 6 kHz

Gas:
0.1 - 40 Torr gradients
He; Xe, N_2, Ar, Kr,, … admixtures
(for narrow-band radiation source)

Experimental set up





Example of central part of the simulated geometry

Capillary discharge dynamics & emission features:

E-beam, plasma channelling (ε>>1)

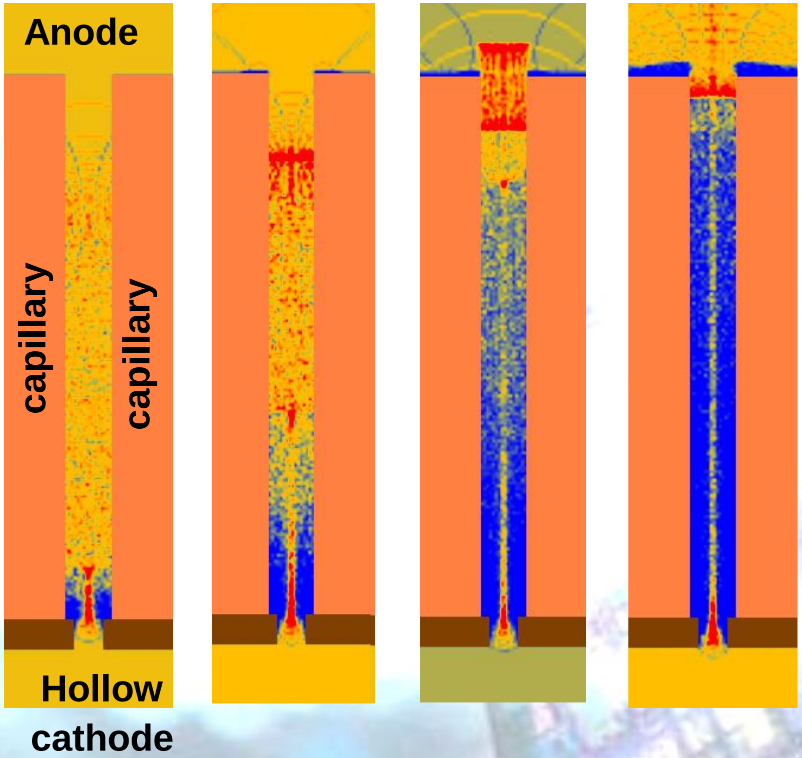
Volumetric MHD compression (skin depth >>plasma diameter)

Highly ionized ions (fast electrons)

Hollow-cathode Capillary Discharge

triggering by fast electrons

modelling together with KIAM RAS



Electron beam in the HC capillary discharge

⇒ run-away electrons

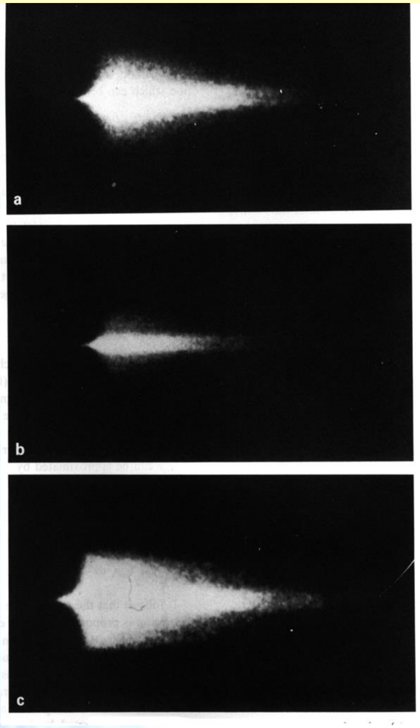
⇒ electric field drops deeper into HC

⇒ e-beam concentration (ε >>1)

⇒ e-beam-gas ionization

⇒ ionization wave

optical streak photograph

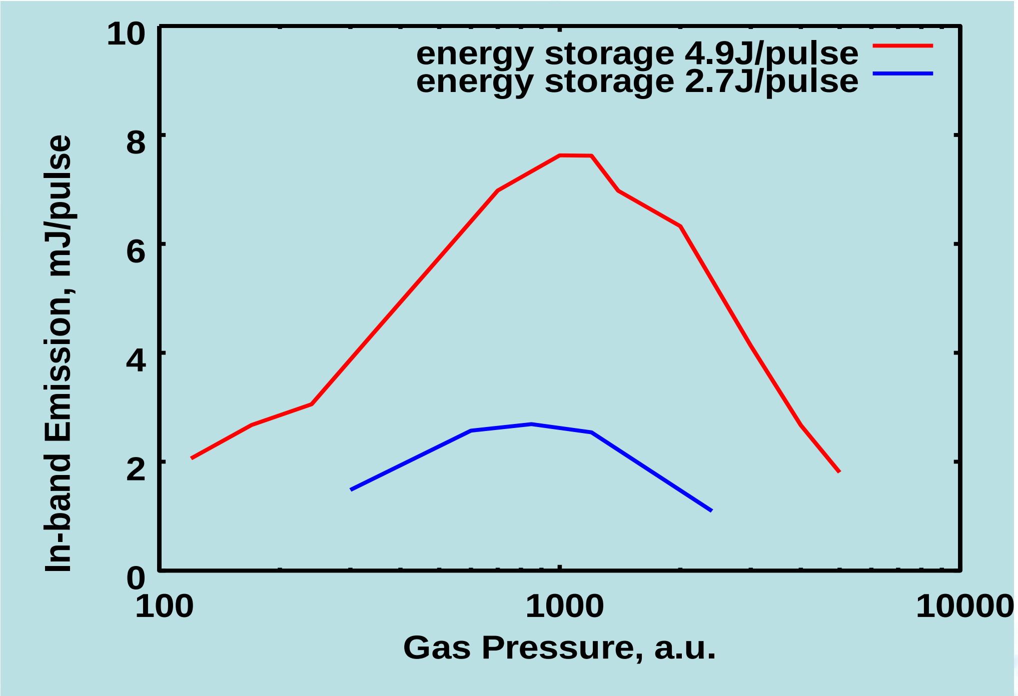


EPPRA, EUVL Symposium, 2002

In the first few nanoseconds, run-away electrons from the hollow cathode generate a tight ionized channel (< 200μm diameter) in the gas

Capillary Discharge EUV Source

modelling source optimization

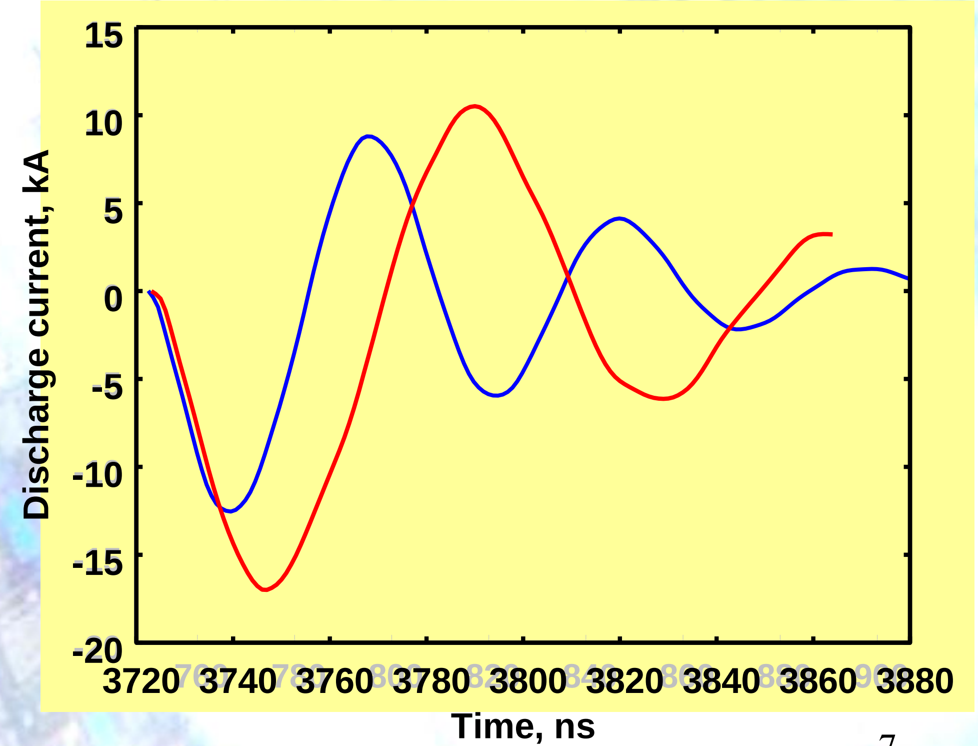


Optimization

by gas mixture pressure

Electric current

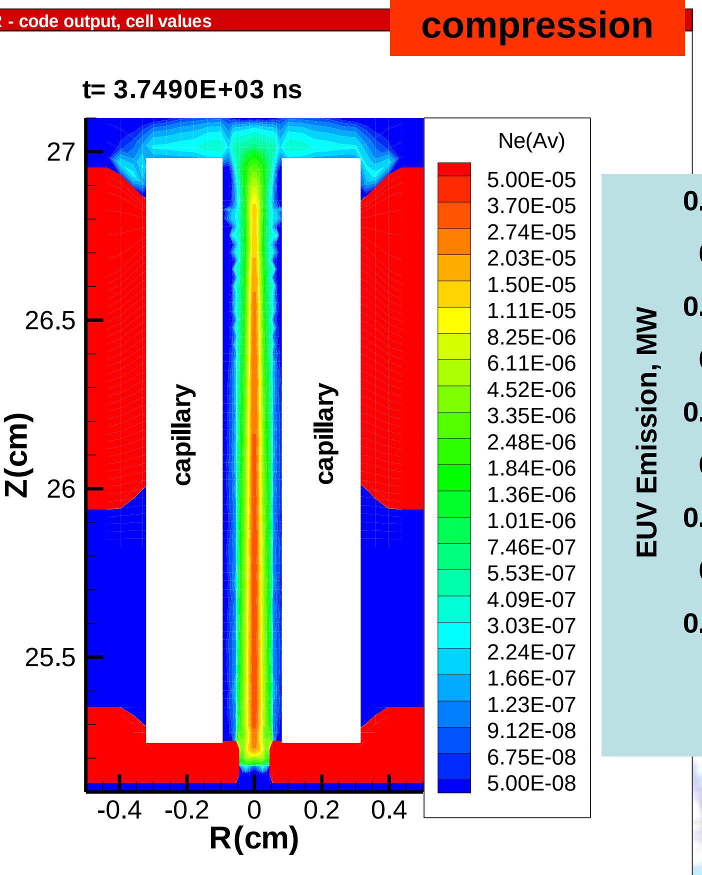
through discharge
at optimums



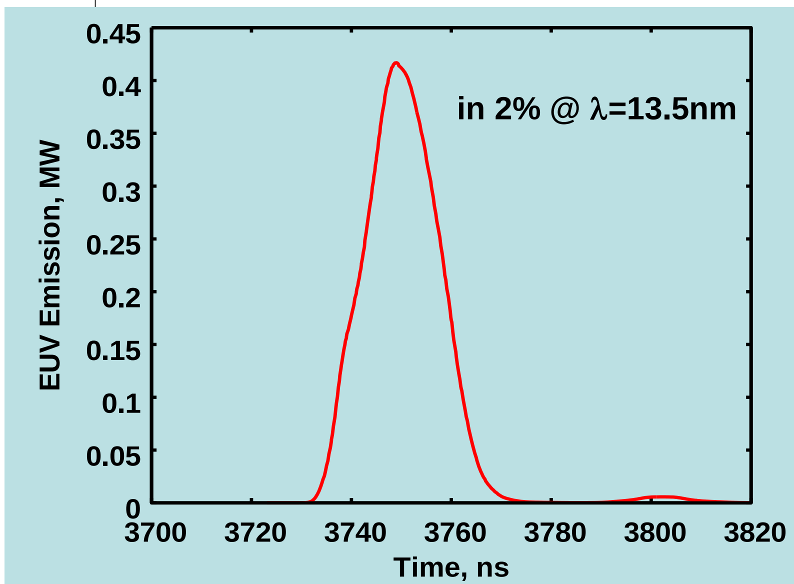
Capillary Discharge EUV Source

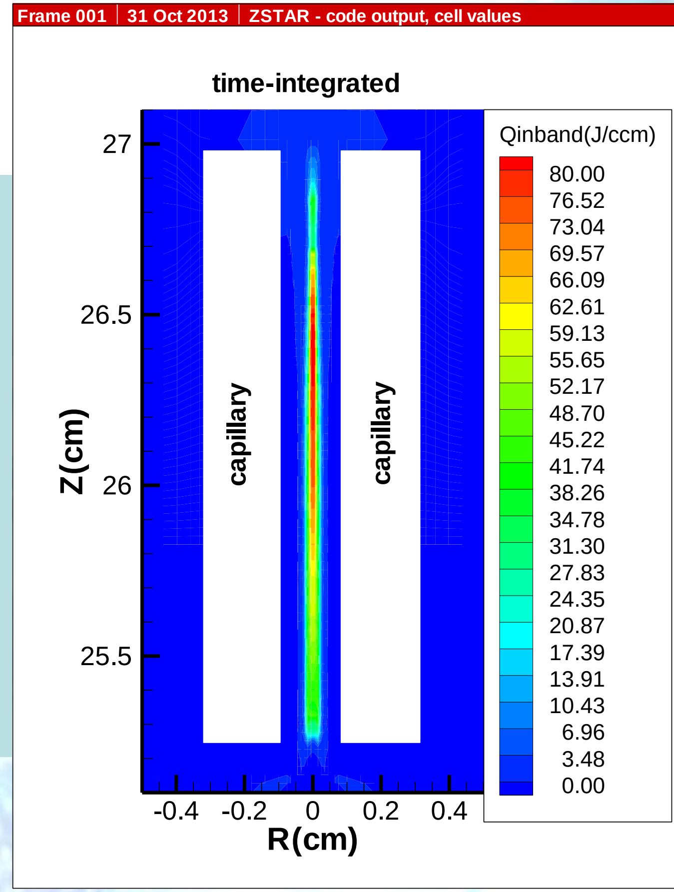
dynamics & EUV emission

3D volumetric compression



N_e=1-1.5 $\cdot 10^{18}$cm^{-3},
T_e=25-40eV.





The traced along the axis, EUV intensity in 2% band at 13.5nm wavelength

60 W/mm^2 sr per kHz

Calculated in-band EUV emission

7.6 W/kHz in 2π

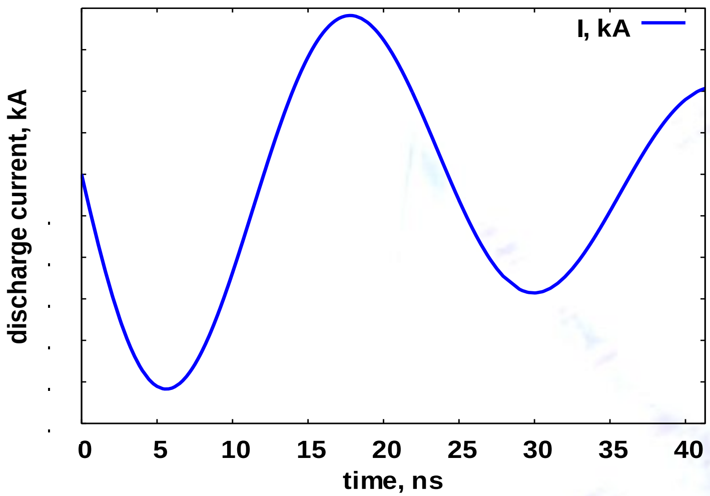
EUV source cross-section

Source diameter 0.16mm

Further optimization of the source

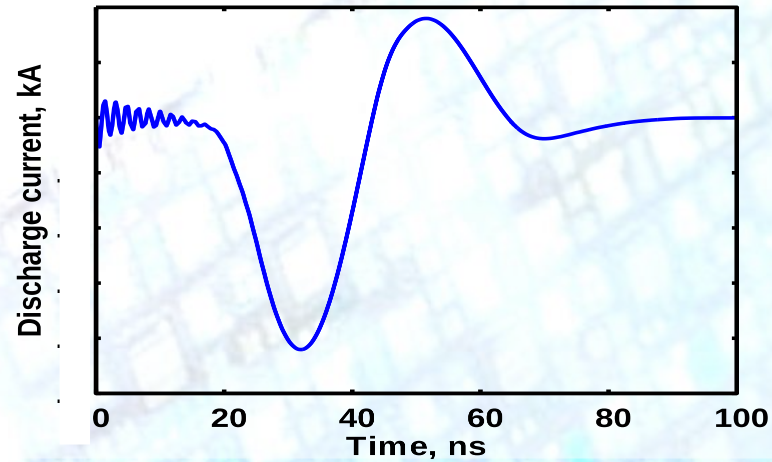
switching from inductive to resistive regime

Inductive regime



Nitrogen as buffer gas

Resistive regime

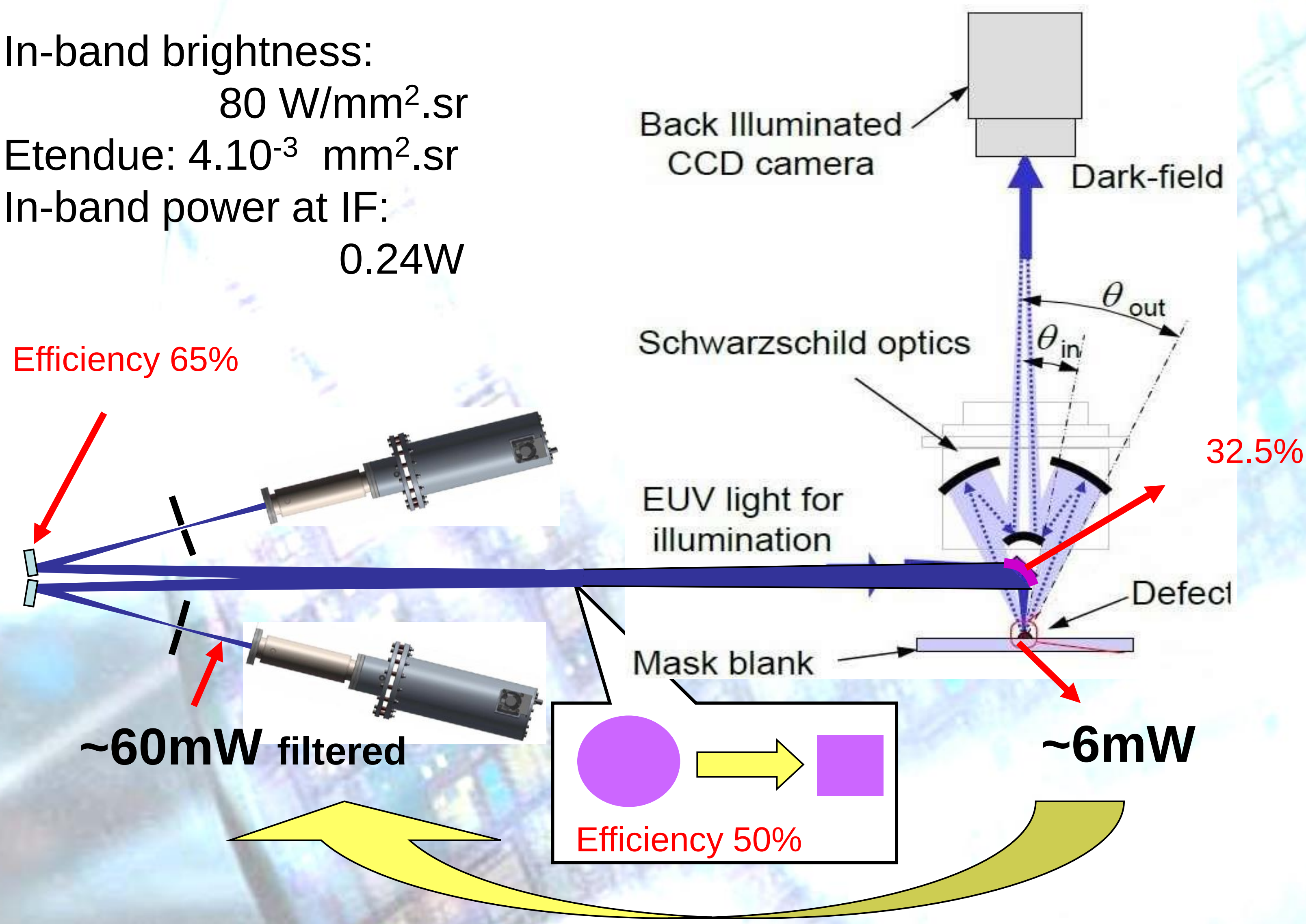


In the resistive regime of capillary discharge, the high joule dissipation in the tight conductive channel produced by hollow cathode electron beam creates an efficient mechanism of plasma heating and EUV or soft X-ray emission.

Also, fast electrons increase the ionization degree of heavy ions (Xe,…) plasma increasing eo ipso EUV yield.

Example of double unit EUV source for ABI

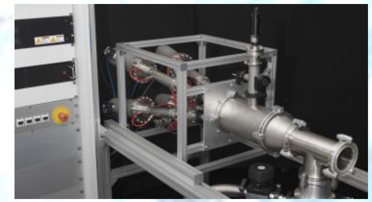
In-band brightness:
80 W/mm^2.sr
Etendue: 4.10^{-3} mm^2.sr
In-band power at IF:
0.24W



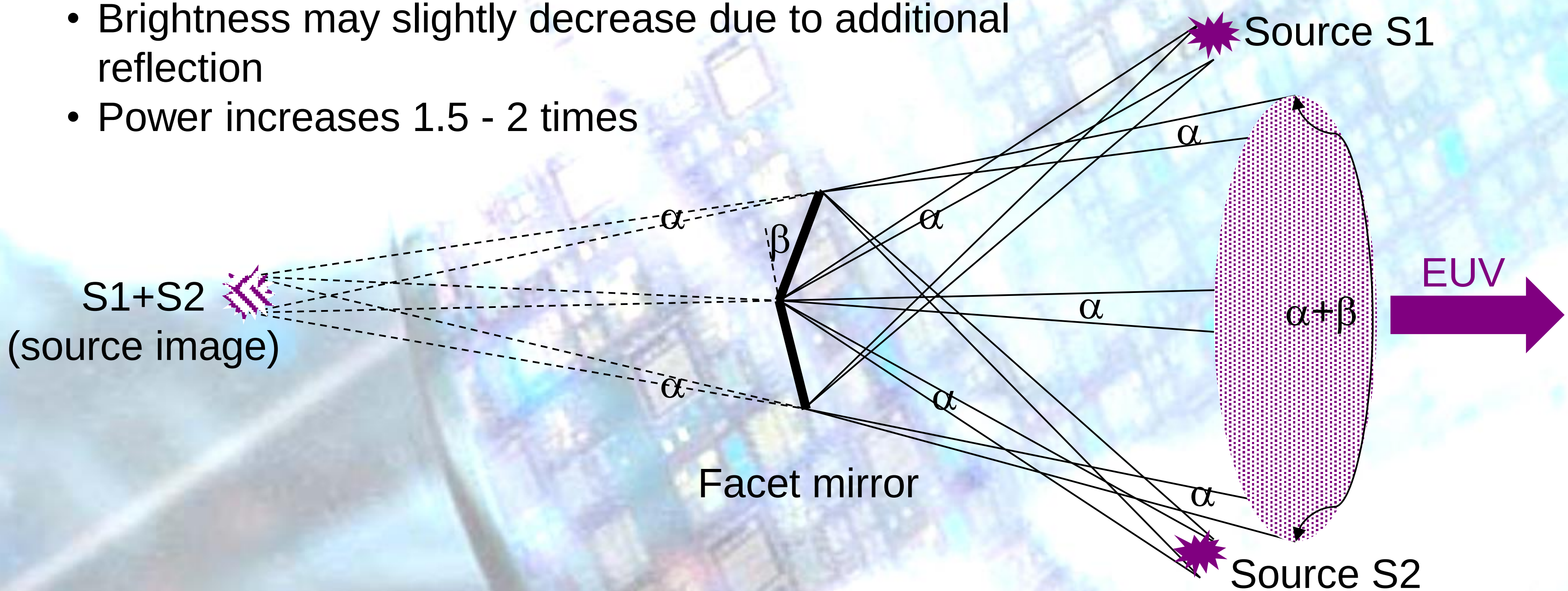
Spatial mutiplexing

- static combination of 2 beams into one beam

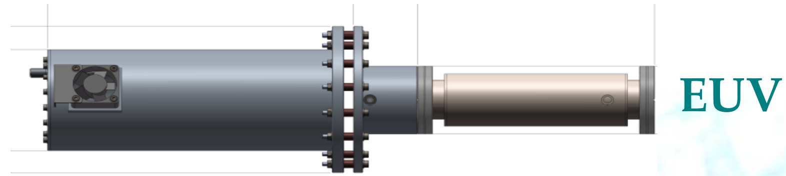
- Etendue of a single source is $E_1 \approx \; S \cdot \frac{\pi}{4}\alpha^2$
- IN FAR-FIELD the etendue of 2 equivalent sources is
  $E_{2FF} \approx 2S\cdot \frac{\pi}{4}(\alpha+\beta)^2 \approx 4\ E_1$



- IN NEAR-FIELD the declination due to β can be corrected and the etendue of 2 equivalent sources is
  $E_{2NF} \approx 2S\cdot \frac{\pi}{4}\alpha^2 \approx 2\ E_1$
- Brightness may slightly decrease due to additional reflection
- Power increases 1.5 - 2 times



Sources for AIMS or APMI



AIMS source requirements

30-100 W/mm^2.sr in-band

Etendue 5.10^{-4} mm^2.sr

In-band power at IF 15-50 mW

- Proposal

  1 source

APMI source requirements

In-band brightness : 40-80 W/mm2.sr

Etendue: 1.5.10-2 mm2.sr

In-band power at IF: 0.6-1.2 W

Operation frequency >10kHz

- Proposal

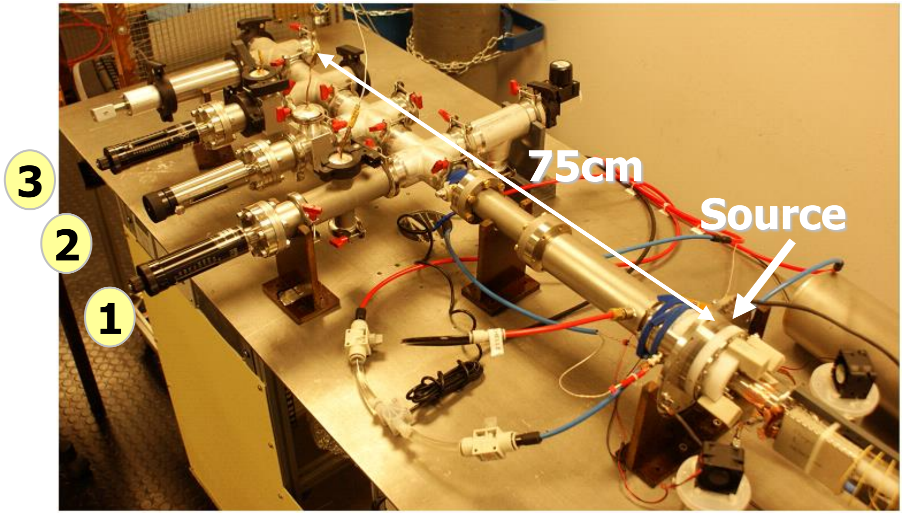
  4 sources temporally multiplexed

  Averaged brightness increases 3-4 times

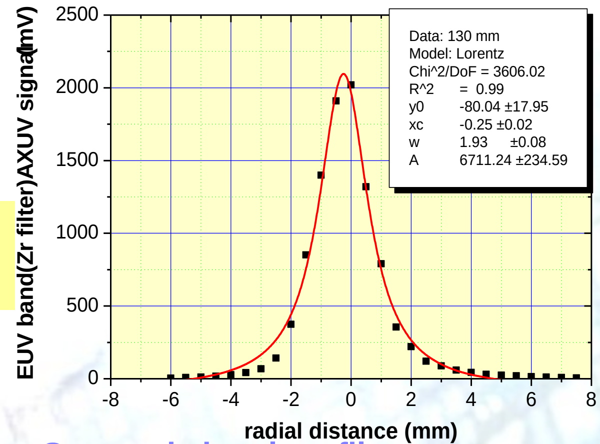
  Averaged power increases 3-4 times

  (grazing incident optics or ML mirror optics)

Focusing effect observation

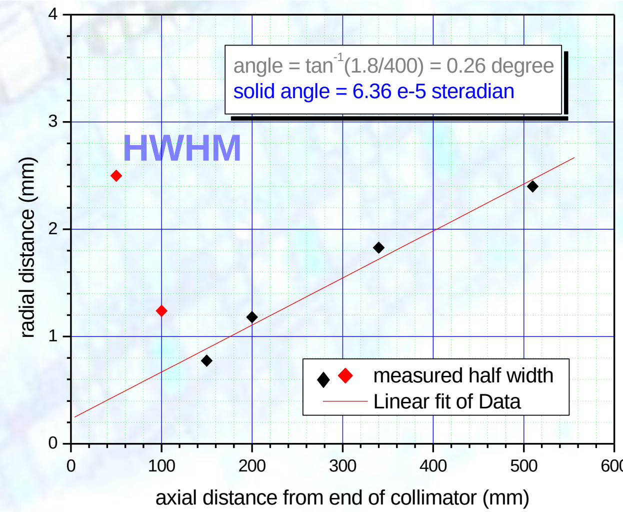


EPPRA measurements



Scanned signal profile

EUV band (Zr filter) radiation beam profile at 130mm from collimator exit



$$n^2 = 1 - \frac{\omega_e^2}{\omega^2} f_1(\omega)$$

δn = /1-n/<<1;

δn ~ 0.01 ÷ 0.05 **(in solid matter) and**

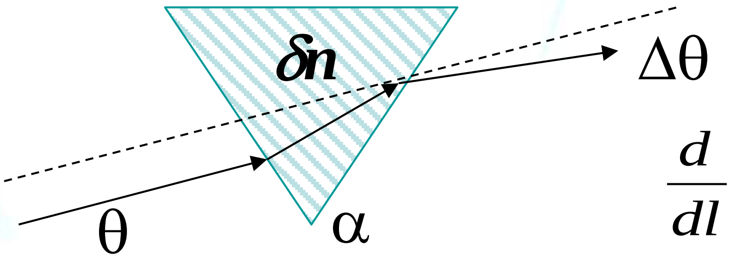
δn = 0.0000…. **(in plasma) for EUV range**

How it is possible in geometrical optics?

Know - How

Wave-guiding refractive structure

NAEXTSTREAM



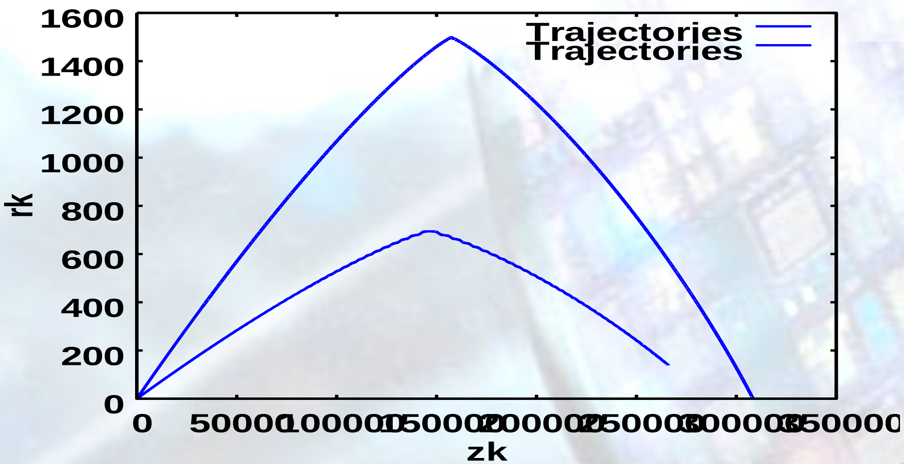
$$N = \frac{\theta}{\delta n \cdot \sin(\alpha)}$$ **refractions are required**

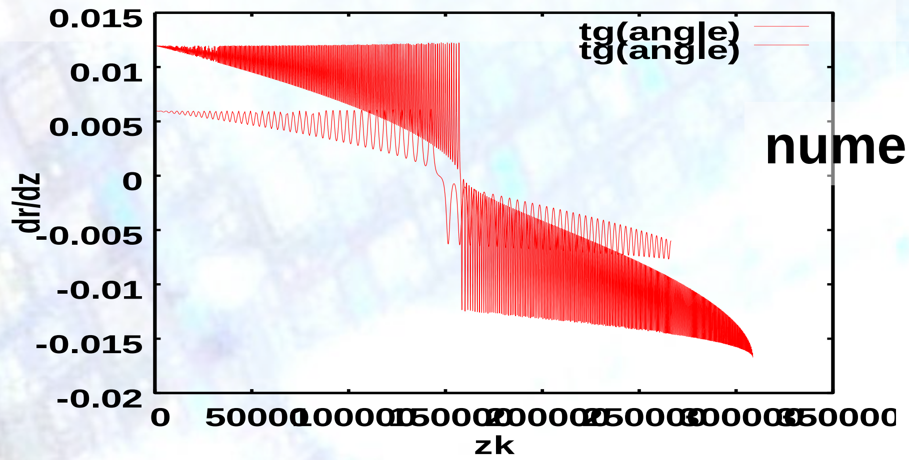
$$\frac{d}{dl}\left[n(\vec{r})\frac{d\vec{r}}{dl} \right] = \vec{\nabla} n(\vec{r})$$ **light trajectory equation**

Refractive Structure:
e-beam generates plasma-acoustic waves, $k \leq r_D^{-1}$

Focussing :

$$\bar{\theta}(z) - \theta_0 \approx -0.25 \int \frac{k_r |\delta n|^2}{\left(1 + 0.5 \frac{k_r^2}{k_z^2} |\delta n|^2\right)} dz$$ **analytical**

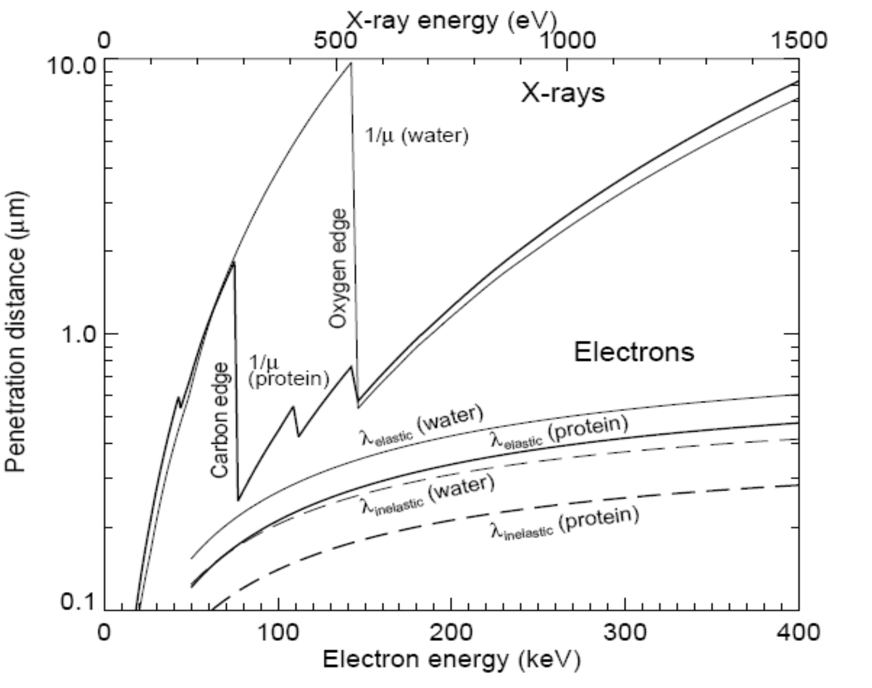


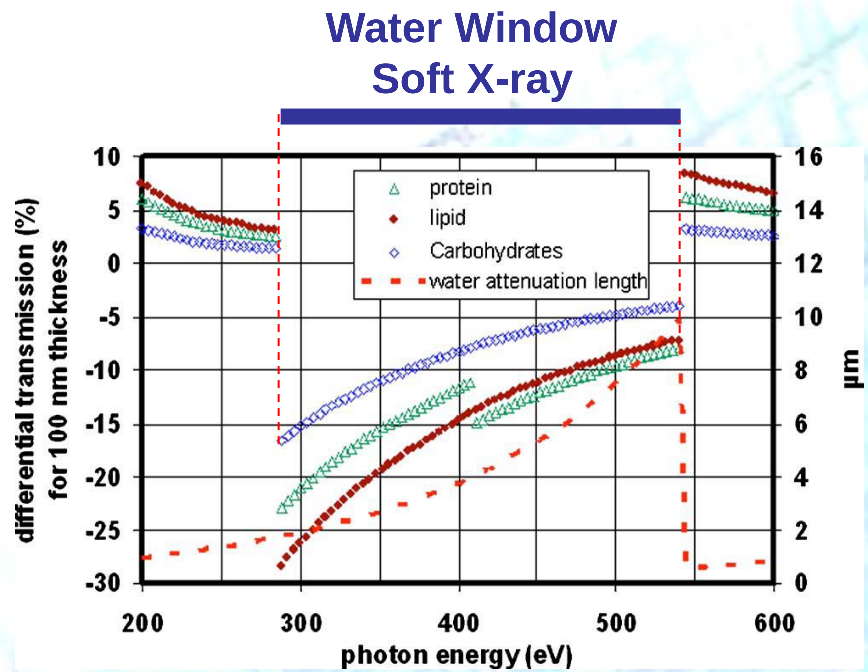


numerical

Source for soft X-ray microscopy

deep penetration & high contrast





Soft X-ray microscopes and their biological applications
Janos Kirz, Chris Jacobsen & Malcolm Howells
- Q. Rev. Biophys. 28, 33{130 (1995)

Table-top water window transmission x-ray microscopy: Review of the key issues, and conceptual design of an instrument for biology.
Jean-François Adam and Jean-Pierre Moya, Jean Susini
- Rev. Sci. Instrum. 76, 091301 2005

N_2, Kr, Zr, Bi, … High Energy Density plasma (T_e=80-200eV) radiates in WW range

poster: Vassily Zakharov "Radiative Properties of Krypton Plasma & Emission of Krypton DPP Source in Water-Window Spectral Range"

Thank you
for attention !

www.naextstream.com